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Electronics for Li-ion Battery Packs in Electric Vehicles

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Abstract

As the number of electric vehicles (EV) increases, so does the demand for automotive battery systems. Battery systems for EV have specific needs, which in turn put extra requirements on all parts used in the system. The paper will highlight some of these requirements for the electronic part and, more specifically, the requirements for the battery monitor / controller of a Li-ion battery-pack.

Based on these requirements, we will focus on a possible implementation and architecture of the battery monitor / controller. The main part of the paper will discuss the HV-requirements, the precision of the different sub-blocks and the required redundancy to guarantee fail-safe operation.

Keywords: Lithium battery, battery management, safety, semi-conductor

1 Introduction

As the number of electric vehicles (EV) increase, the demand for automotive battery systems also increases. Battery systems for EV have specific needs, putting extra requirements on all parts used in the system. This paper highlights some of these requirements and more specific on the requirements for the electronics for the battery-pack (E-BP).

ON Semiconductor has the ability to combine all these features in High Voltage Mixed Signal integrated circuits, providing low cost solutions in automotive qualified processes.

Starting from a general architecture for the battery system (BS) and the specific requirements for automotive battery systems, this paper will present a possible solution to realize and integrate E-BP within the system.

These solutions are based on existing IP and huge expertise in integrated circuits for automotive applications in general as well as for battery systems. Existing IP includes HV protection and regulation, accurate voltage measurement, standard automotive communication transceivers, cost optimized solutions for communication inside stacked battery systems at voltage levels outside the operating voltage of the ASIC or ASSP, and many others...

2 Battery system

2.1 Battery systems within EV

A typical battery system (BS) for EV, looks like depicted in Fig. 1.

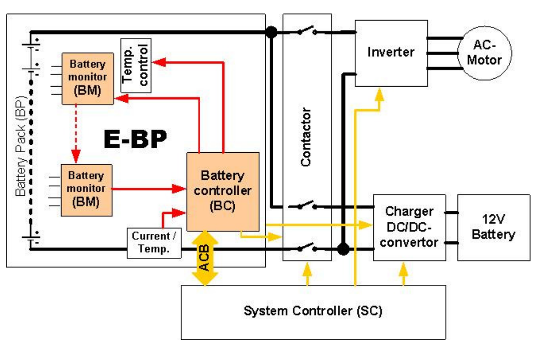

Figure 1: Typical battery system

The E-BP monitors the battery conditions and sends data to the system controller (SC). The SC uses this data to control the contactor box, inverter and charger in a way that optimizes the energy use of the whole system. The E-BP directly controls the contactor box and charger in the event of an emergency. The E-BP controls the blower or water-pump as part of the cooling system, which brings the battery-pack within the ideal thermal conditions.

Different kind of batteries could be used within EV or HEV but this is not part of the expertise within ON Semiconductor. We are involved in the electronic part and more specific in the integrated circuits required for an optimal implementation of the electronics for the BP (E-BP).

This paper will concentrate on the requirements of E-BP and a possible implementation of the different sub-blocks. The paper will only discuss a part of the electronics for the battery-pack (E-BP), namely the central controller (BC) and the battery monitors (BM) which measure the cell-parameters.

2.2 Electronics for the BP (E-BP)

The E-BP has following functions:

1) **Monitor** voltage, current and temperature.
2) **Calculate** state of charge (SOC), state of health (SOH), battery impedance (R act) and remaining capacity (RM).
3) **Protect** against over/under voltage, excessive current, over-heating, and leakage.
4) **Control** of contactor box (in case of emergency), cooling system and charger.
5) **Communication** from battery pack (E-BP) towards system controller (SC) and diagnostic tools (not indicated) by means of some standardized automotive communication bus (ACB).

The **monitoring function** requires high precision sensing and signal processing. The realized accuracy determines the precision for the parameters like state of charge (SOC), state of health (SOH), battery impedance (R act) and remaining capacity (RM). These parameters are required to extend lifetime, improve reliability and deliver improved diagnosis. These functions are realized by complex state machines and embedded micro-controllers.

The battery-pack can contain up to 80 cells in series, which gives a **total voltage of up to 340V**. For the battery controller this means: Wide operating voltage range up to 340V with on top of it HV Transients during charging by the charger and discharging by different kind of loads.

The **protection of the battery pack** is realized by limiting the current and temperature for the whole battery-pack and by limiting and equalizing voltage and by controlling leakage on cell-level. This requires a dedicated partitioning of the different measurement blocks of the E-BP and adequate communication between the sub-blocks of the BC. This communication is by preference realized via an **automotive standard communication bus**.

The E-BP has to **guarantee safe operation** or a controlled shut-down under all conditions. These conditions can involve abnormal conditions, like car-crash, or abnormal use, like short circuit. Save operation has also to be guaranteed in case of failures on any of the components, on the PCB's or any of the interconnections. This will require **redundancy** at component-, circuit- and system-level.

2.3 Parameters determined by the BC

Many parameters exist for determining the performance of the battery. Some of them can be measured directly, others are a good measure to determine the quality or indicate the remaining lifetime of the battery [1].

Some examples are listed below:

- SOC (State of charge) = Q remain / Qmax
  Qmax = Fully charged coulomb capacity
  Qremain = Remaining coulomb capacity
- R act (actual battery impedance)
  = │V average – OCV│ / I average
- SOH-R (State of health based on impedance) = R aged / R new (>1)
- SOH-Q (State of health based on maximum charge) = Qmax aged / Qmax new (<1)

The measurement of the SOC is very important but also very difficult. SOC changes with aging and temperature and can be determined as follows.

For the unloaded battery, the remaining capacity (SOC) is indirectly given by the open circuit voltage (OCV). Li-ion batteries show a good relationship between the voltage curve and the SOC. An example is depicted in figure 2. This relation is different for different battery chemistry. For Li-ion batteries, this relation is quit accurate because these batteries show a very small memory effect (high efficiency). Some difference can be observed depending of the cathode and anode material.

Li-Mn-O: Typ. Volt. = 3.6V
50mV / 10% SOC
Li-Fe-PO: Typ. Volt. = 3V
25mV / 10% SOC
LiCo – Ti: Typ. Volt. = 2.3V

Li-Fe-PO – Ti: Typ. Volt. = 1.9V
10mV / 10% SOC

This indicates that the measurement for OCV requires very high precision or more specific, the accuracy of the voltage-measurement has to be better then 0.25% to realize an error in capacity lower then 5%. We will come back on this point when we discuss the sub-blocks of the battery monitor (BM).
During load conditions, SOC can be estimated based on the integrated current.
SOC-2 = SOC-1 + dQ/Qmax
$dQ = \int Ic\, dT \times \eta - \int Id\, dT$ (Ic : charge current, Id : discharge current, η : Charge efficiency > 90%)
Some settling has to be taken into account.

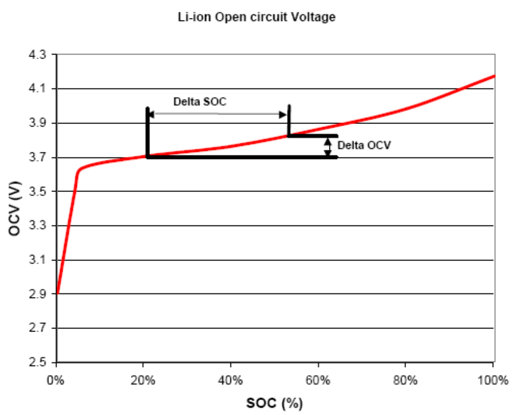

Figure 2: SOC dependency on OCV

The impedance of the battery cell is determined by the following formula:
Actual Battery impedance:

$$R\ act = \left| V\ average - OCV \right| / I\ average$$

AC-impedance:

$$R\ AC = Delta\text{-}V / I\ average$$

(V average : average voltage, I average : average current).

The typical resistance of a battery-cell is in between 1mOhm and 10mOhm depending of the construction and capacity of the cell. This resistance is however depending on temperature, SOC, aging of the battery-cell and cycling of the battery.
Figure 3 gives an indication of the different contributions of the cell-resistance. The cell-resistance is partly depending of resistive materials like the collectors and partly depending of the ionic diffusion speed. This makes the resistance function of time and makes it more difficult to measure without defining appropriate settling times. The measured impedance is sometimes used as an indication for the aging of the battery and to predict the remaining lifetime of the battery-cell or in other words SOH. A practical implementation will either use look-up tables or battery-models to determine SOH based on input-parameters: temperature, R-measured, V-measured.

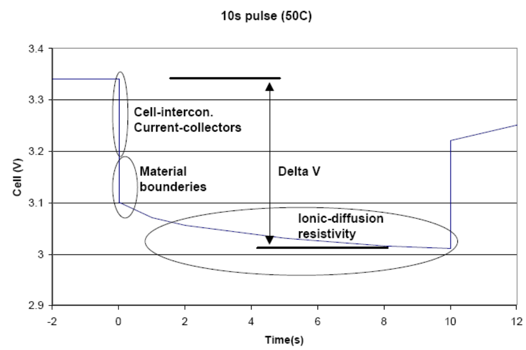

Figure 3: Cell-voltage in function of time

An alternative way to measure the aging of the battery is to determine Qmax (Fully charged coulomb capacity). This parameter can not be measured directly because in most cases the battery will operate between 40% and 60% SOC. But Qmax can be calculated based on 2 different SOC measurements at two different arbitrary points.
SOC = Q remain / Q max
SOC-1 – SOC-2 = dQ / Q max
Qmax = dQ / (SOC-1 – SOC-2) with dQ the integrated current between SOC-1 and SOC-2.
For the measurement of R and Qmax, only the relative accuracy of the cell-voltage is important. This is mainly determined by the accuracy of the ADC. An accuracy of 12bit should be sufficient and is still practical to realize.

2.4 Sub-blocks for E-BP

The electronics for the BP (E-BP) are built of several sub-blocks. For the following discussion, we only consider the monitoring function of the BC. The protection function is indirectly discussed because they use the same functional sub-blocks.

An example of the implementation of electronics part is depicted in figure 1.

The calculations for SOC, SOH, R act and Qmax are performed within the battery-controller (BC). The measurements of current, temperature and cell-voltages are performed in dedicated circuits.
The voltages of different cells are measured by the different battery monitors (BM's). The number of cell-voltages measured by one BM can very between 4 up to 12 depending of the used HV-technology.
The interface between the BM's and the main-controller is performed by the insulation couplers (I/C) which could be opto-couplers for slow signals or digital insulators for faster signals. Also for the bottom BM, these I/C are recommended due to the high voltage transients on the ground of the battery-pack and to avoid damage in case of ground-loss. Ideally, a full isolation between the HV-part and the low-voltage part should be realized.
The communication between the different BM's and the BC happens through a dedicated daisy-chain communication bus. This dedicated bus has to be robust towards automotive transients and has to realize the required throughput for an acceptable cost. The requirements for this communication bus are discussed in the next paragraphs.
The temperature sensors are distributed over the whole battery-pack and are for this reason localized in the BM. The temperature-sensor is close to the cells and is connected to the corresponding BM, within the battery-pack. Every BM can accommodate different temperature-sensors or can have one temperature sensor for each cell.

2.5 Battery monitor (BM)

The battery controller monitors the battery cells by means of different BM's.
The following functions are localized in the BM:

- Measurement of cell-voltage:
  - **Pre-amplifier** to level shift and down-convert the cell-voltage (within the range of the ADC).
  - **ADC**: converts analogue cell-voltage in digital value.
  - **DSP**: for filtering, averaging, offset-cancellation and gain-correction
- Cell balancing fully controlled by BC.
- Communication with BC.

Following blocks supports these functions:

- Voltage reference: determines the absolute accuracy of the measurement.
- Internal RC-oscillator: as time-base for measurement and communication.

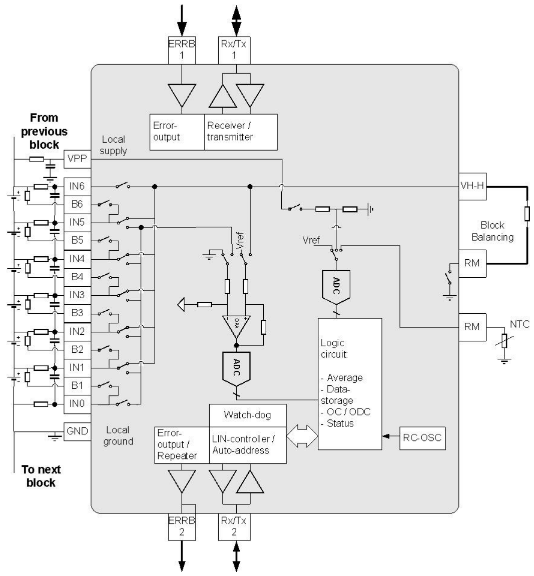

Figure 4: Block diagram for BM

The BM requires a dedicated silicon technology.
It requires high-voltage capability to cover as many cells as possible by one BM.
Let's look to an example:
Battery pack with 90 cells
=> Total voltage of battery pack
= 90 x 3.6V = 325V (nominal)
On top of this voltage, we get voltage transients, e.g. regenerative braking
=> Maximum voltage up to 400V
= 90 x 4.2V + 100A x 200mOhm < 400V
For a BM with up to 12 cells, this gives a voltage range between 34V and 60V.
The LV-part of the BM has to implement the required precision by means of the ADC and the voltage reference and the processing capability of the DSP.
ON Semiconductor has selected one of its SmartPower technologies I3T.
The I3T-technology is based on a 0.35µm CMOS technology extended with MIM-capacitors and HIPO-resistors for analogue capabilities. The technology and components are optimized for analogue signal processing e.g. matching to allow high precision sensor implementation.
The high-voltage part of the I3T-technologies includes N-DMOS, P-DMOS and bipolar transistors. These devices are fully floating towards ground and are protected by internal

structures and dedicated ESD-protections. Floating structures do not mean only +50V or +80V but can also mean –50V or –80V depending of the implementation and the customer requirements.
The voltage reference, balancing, the communication-block and redundancy will be discussed in the next paragraph in more detail. Some other blocks are shortly discussed below.

HV-Multiplexer: for selecting one of the battery-cells. The multiplexer is implemented by means of the HV-devices. It has to withstand the transients but has also to avoid any cross-coupling between the different channels.
Pre-amplifier: is also part of the HV-circuitry. It requires a high common-mode input range and requires low offset. It also serves as level-shift to the input of the ADC. Important is to realize a good CMRR (Common-Mode Rejection Ratio) to make sure that it not effects the accuracy of the individual cells.
Internal voltage regulator generates the internal 3.3V supply for the LV-analogue and digital circuit. An external capacitor is used for stability and filtering and to avoid coupling between analogue and digital circuitry.
All the other blocks are implemented in low-voltage CMOS. They include following analogue blocks: high resolution ADC, RC-oscillator, precise voltage reference, temperature sensors and the digital part for the DSP and the communication-controller.
The logic is implemented by means of a dedicated automotive library to minimize EME (Electro Magnetic Emission).

The block-diagram implements also the required redundancy for safety critical applications:

- 2 separate ADC's: one to measure the cell-voltages and one to measure the block-voltage. The total sum of all cell-voltages has to be the same as the measured block-voltage.
- 2 separate communication-channels: LIN-daisy-chain and ERRB-daisy-chain
- Watchdog to monitor the 2 communication-channels
- …

3 ON-semi-IP's for BM

This paragraph discusses in more detail following IP's (Intellectual Properties):

- Voltage reference
- Balancing
- ACB (Automotive communication bus)

3.1 Voltage reference

The voltage reference (Vref) plays an important roll within the BM. Its accuracy determines the accuracy of the measured cell-voltage and the accuracy of the derived parameters: OCV, SOC, SOH, Ract, RM and others.
Like mentioned above, an accuracy of 0.25% on the measured voltage gives an error of 5% on the calculated SOC. This is an important challenge that is discussed below.
A bandgap reference based on bipolar transistors shows a temperature behavior like shown in figure 5. The different curves are realized by changing the current of the bipolar current-mirror.

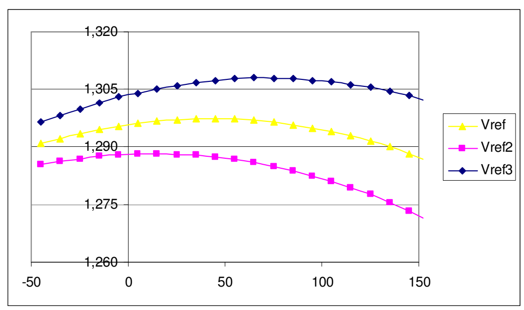

Figure 5: Typical bandgap behavior with bipolar tr.

Including the matching of the components, we will get a tolerance of +/- 2% including tolerance at room-temperature but also temperature behavior between –40ºC and + 125ºC.
This behavior can be improved by wafer-trimming and by secondary temperature compensation. This results in an overall tolerance of better then 0.5%.
The trimming correction factors are stored in OTP (One-Time-Programmable memory) during test of the packaged components.
Adding to this voltage reference tolerance, the offset-error, the gain- and offset-error of the ADC and the effect of the common-mode voltage of the differential amplifier, we can realize an overall absolute tolerance of the signal-path of +/- 1%.
This accuracy is however still not acceptable for some battery chemistries. A better accuracy can be realized through in-system-calibration. This in-

system-calibration is not depicted in the block-diagram. This dedicated IP gives an improvement for the absolute cell-measurement with at least a factor 4.

3.2 Cell-balancing

The circuitry that balance cells and eliminate mismatches of cells in series significantly improve BP efficiency, increase overall BP capacity and increase lifetime of the BP. As the number of cells (up to 90 cells for full-hybrid) and load currents increase (up to 50C or 100C), the potential for mismatch also increases. There are two kinds of mismatch in the pack: State-of-Charge (SOC) and capacity/energy (C/E) mismatch. Though the SOC mismatch is more common, each problem limits the pack capacity (mAh) to the capacity of the weakest cell.

It is important to recognize that the cell mismatch results more from limitations in process control and inspection than from variations inherent in the Lithium Ion chemistry. The use of cell balancing can improve the performance of series connected Li-ion Cells by addressing both SOC and C/E issues. SOC mismatch can be remedied by balancing the cell during an initial conditioning period and subsequently only during the charge phase. C/E mismatch remedies are more difficult to implement and harder to measure and require balancing during both charge and discharge periods.

The balancing circuit indicated on the block-diagram of the BM bypass some of the current through balancing resistors. The balancing resistors are put external due to the high dissipation. The switches are integrated in the BM.

This way of balancing, during charging, is only effective when all cells have approximately the same capacity. They are balanced when they have the same relative State of Charge (SOC.) In this case, the Open Circuit Voltage (OCV) is a good measure of the SOC. Once the cells are balanced, then they will subsequently cycle normally without any additional adjustments. This is mostly a one shot fix.

If however the cells have different capacities, they are also considered balanced when the SOC is the same. But, since SOC is a relative measure, the absolute amount of capacity for each cell is different. To keep the cells with different capacities at the same SOC, cell balancing must provide differential amounts of current to cells in the series string during both charge and discharge on every cycle. This way of balancing requires more complex algorithms to measure the effective capacity of each cell and will require more dedicated balancing circuit. A DC-DC converter based on an external inductor can accomplish such task and can further improve the balancing and lifetime of the battery-pack.

3.3 Automotive communication bus (ACB):

The automotive communication bus between the BC and the BM's is implemented as a daisy-chain. The principle schematic is depicted in figure 6.

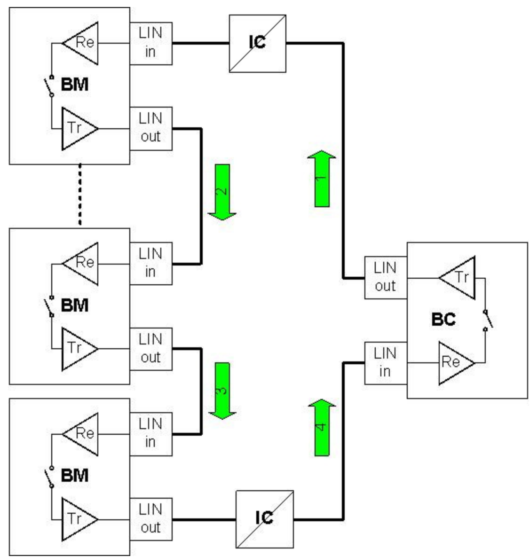

Figure 6: Principle schematic for daisy-chain implementation

The daisy-chain has following advantages:

- Minimize the use of I/C's. 2 sets of IC's are required to interface to the top and the bottom BM.
- Auto-address-assignment during initialization.
- Extra fault-tolerance realized through the closed loop daisy-chain. The command send by the BC at LIN-out is compared with the response received by the BC at LIN-in.

The implemented ACB can be based on the LIN-protocol (or other automotive communication protocol). The physical layer implementation is tailored to the needs and requirements of the BP.

The low cost target of this automotive bus is realized by following factors:

- single master and multiple slaves

- simplified protocol controller based on UART
- Time-triggered protocol without acknowledge bit or error-byte so that no strict delay-specifications are required.

A typical LIN-frame is depicted in figure 7.

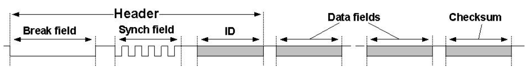

Figure 7: Typical LIN-frame

The frame starts with a break-field which indicates the start of the frame. This brake-field allows a simple way to recover the communication after any disturbance on the ACB.
The second byte is a synch-field that is required to synchronize the clock of the slave (BM) to the clock of the master (BC) to guarantee a reliable communication. Before synchronization, the internal time base requires an accuracy of +/- 14%. After synchronization, the accuracy of the time-base is better then 2%.
The third byte, the identifier, contains information about the command and about the address of the slave. This address is unique for every slave and is used by the master, the BC, to address one specific slave.
The data fields are used to write data to the slaves and to read data e.g. cell-voltage from the slaves. The final byte, the checksum, offers some minimal robustness towards disturbances.
The required throughput for the ACB is based on following assumptions:

- All cells are measured with a relative accuracy of 12 bit.
- The BC controls the balancing of every cell => log2 (n) bits to select each cell (n number of cells monitored by one BM)
- Status information from the BM
- Measured temperature: 8 bit accuracy

A rough estimation based on the LIN-frame composition and the required information-data gives a required data-stream of 27 bits / cell.
Supposing, we want to measure all cells within 10ms and supposing that the BP contains up to 90 cells, we can estimate the required baud rate:

Required baud rate = 27 bits/cell * 90 cells / 10ms = 250 kb/s

It is clear that such baud rate cannot be realized with the standard LIN physical layer and requires a dedicated implementation.

Some other communication protocols provide higher bit-rate and higher robustness and will be a better candidate. The ACB does however not require the overhead of a multiple master's protocol and event-triggered bus-arbitration like foreseen by CAN.

3.4 Required redundancy for fail-safe operation:

The E-BP has to **guarantee safe operation** or a controlled shut-down under all conditions. These conditions can involve abnormal conditions, like car-crash, or abnormal use, like short circuit between two PCB-tracks. Save operation has also to be guaranteed in case of failures on any of the components, on the PCB's or any of the interconnections. This will require **redundancy** at component-, circuit- and system-level.
An expensive solution could be to duplicate the daisy-chain of monitoring devices like depicted in Fig.8.

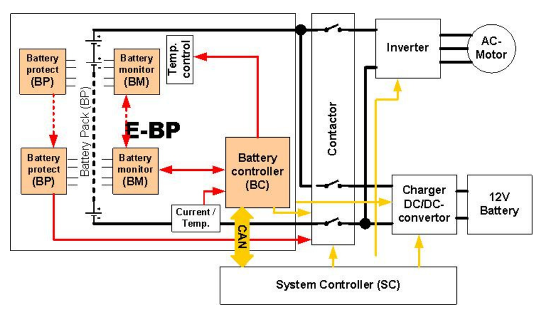

Figure 8: Redundancy by multiple daisy-chains: one daisy-chain for cell-monitoring (BM) and one daisy-chain for cell-protection (BP)

The extra daisy chain, of protection devices (BP), can bypass the batter-controller to open the contactor in case of emergency (faster reaction time). The extra protection devices can be avoided by including extra redundancy for the monitoring devices leading to required robustness for the overall system. The performance of the redundancy is analyzed extensively by System Failure Mode and Effect Analysis (SFMEA) and Fault Tree Analysis (FTA). The extensive discussion of this analysis is out of the scope of this paper. Some examples of implemented redundancy are listed and discussed below:

- Two signal paths, cell-measurement and block-measurement (group of all cells) like indicated in Fig. 4. The logic performs the corresponding redundancy-check on the obtained measurement results.

- Two daisy-chain channels like indicated in Fig. 4. One daisy-chain channel RX/TX to communicate measured data to the main-controller and one daisy-chain to flag errors without any delay: over-voltage, under-voltage, watch-dog time-out, self-test error.
- Open-connection detection for every cell-input to avoid wrong cell-measurements.
- Build-In-Self-Test for logic (Logic BIST).
- Build-In-Self-Test and calibration for signal path.

By all this added redundancy, we can guarantee the functionality of the monitoring devices but how can we guarantee the accuracy of every voltage reference of each individual monitoring device? Like mentioned above, the required accuracy of the voltage reference is of major importance for the required performance of the individual monitoring device.

One possibility is to add an extra external precision voltage reference for each monitoring device and to add an extra ADC-channel. This gives extra cost and extra complexity but the required redundancy.

ON Semiconductor has chosen for an other possibility which profit from the daisy-chain implementation. This implementation is not indicated in Fig. 4. and adds extra complexity for the monitoring device. It gives the required redundancy for the voltage reference and will avoid the use of an extra external precision voltage reference for each monitoring device.

4 Conclusion

This article has given an overview of the different parts of the battery system within HEV. Within the battery system, we have focused on the electronics of the battery pack and on the different parameters to realize the performance of the battery system.

Based on these requirements, we have proposed a possible implementation of the electronics and have discussed a possible implementation for the battery-monitor (BM).

Finally, we covered the technology requirements and the specific ON Semiconductor-IP's, which enable a cost effective integration of the battery monitor (BM). The implementation gives extra focus on the build-in redundancy to guarantee fail-safe operation.

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